FUNGI
AND THEIR APPPLICATIONS

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Abstract:

Fungi are eukaryotic organisms with the potential of being utilized in each sector for human benefit. Primarily, they are decomposers and play a vital role in scrubbing the waste matter from the environment. Fungi are ancient beings, with recorded occurrences dating to the Late Crustacean period. Fungi illustrate significantly high diversity in terms of morphology and distribution. They survive in close association with their surrounding environment and aid in solving many environmental-related issues such as oil spills, climate crises, etc. Fungi can efficiently improve the soil profile by promoting nutrient recycling in the soil. A specialized kind of root–fungal association termed “mycorrhiza”, improves the soil structure, restricts the growth of pests, improves growth patterns and yield, and enhances the nutrient uptake by plants from the soil. Fungi manifest more biodegradability of hydrocarbons as compared to enzymes or bacteria. Several fungi (especially mushrooms) are utilized globally as a medicine for the treatment of several cancers, diabetes, obesity, and weight loss. Mushrooms are also known to serve as food for brain synapses. Mushrooms are further explored for their potential role in controlling severe neurological disorders such as Alzheimer’s and Parkinson’s disease. Fungi essentially form a major component for controlling plant diseases and have proven to be a better alternative to chemical pesticides and insecticides. Owing to the limitless advantages of fungi, several industrialists, for quite a time now, are attracted to the cultivation of fungi on a large scale, mainly for food production, biofertilizers production, antibiotics production, and/or secondary metabolites production. Although fungi grow under less stringent environmental parameters, certain parameters such as temperature, pH, dissolved oxygen, cultivation media, etc., need to be optimized, depending upon the fungi of interest to obtain the maximum yield. Fungi is one of the most important factors for maintaining ecological balances and substantially preventing the deterioration of the environment.

Keywords: Mycorrhiza, Mushrooms, Biocontrol Agents, Oil spills, Nutrient recycling, Antibiotics.

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1 Introduction:

A fungus is a eukaryotic organism (having a well-developed nucleus and cell organelles) that externally absorbs the nutrients directly into its cell walls. Fungi are heterotrophic beings and depend upon other organisms for their requirement of carbon and energy. The fungi obtaining the nutrients from the living host such as a plant or animal are referred to as “biotrophs” while the others obtaining their nutrients from the dead plants or animals are referred to as “saprotrophs/saprophytes”. However, some other kind of fungi infect the living host and kills it to obtain the nutrients, and these are referred to as “necrotrophs.”

Fungi were once considered a primitive member of the plant kingdom. However, with the advance in fungal research, it is now known that fungus is not at all primitive. Fungi may not be our next kin but are closely related to animals than to plants (Carries, Little, & Stiles, 2012). They are considered intelligent as they communicate, respond to their surroundings, gather food, and defend themselves.

Largely, the fungi are placed into three true fungal phyla a) Ascomycota, b) Basidiomycota, c) Chytridiomycota and d) Zygomycota. Recent studies have come up with a new fungal phylum – Glomeromycota, which includes the fungi forming an extensive association with the roots of most plants. Likewise, a group of the parasites found in the living cells of the animals called “Microsporidia” is now placed in the Kingdom fungi. However, the classification system constantly undergoes modifications as taxonomist utilizes novel techniques to study fungi. For example, Cryptomycota was defined as a potential phylum of Kingdom Fungi (Jones, et al., 2011).

Fungi are as old as 3.5 billion years (as per the fossils records), however, the earliest fungal fossils that emerged belonged to Ordovician, 455-460 million years ago. The fossils evidence of earlier vascular plants obtained was around 425 million years ago (Redecker, Kodner, & Graham, 2000). Based on this fact, several scientists believe that fungi may have played an essential role in supporting the plants to colonize the land. Mushrooms were believed to be present on earth even during the Late Cretaceous Era (Hibbett, Binder, Wang, & Goldman, 2003). However, the fungal fossil record is not a complete one and provides limited information on the time estimate for when different groups of fungi evolved.

Fungi demonstrate striking diversity, which has been extensively investigated and the number of species has been estimated. With a notable advancement in molecular phylogeny, several unexpected fungal diversities and several fungal operational taxonomic units have emerged in the last decade. The fungal species on the earth are estimated to be 12 (11.7-13.2) million (Wu, et al., 2019), however, the number of formally described taxa is around 150,000, only a small portion of the total number. (Phukhamsakda, et al., 2022). However, the currently available high-throughput sequencing techniques could potentially reveal even a higher diversity than the current estimation. The first-ever achieved exhaustive enumeration of fungi in soil recorded 1002 taxa (Taylor, et al., 2014). The fungi are not only found on the surface of the earth but have extensively colonized below the ground in the soil, as well as in inland water environments and even oceans. Fungi form the second largest group of organisms after insects.

Morphologically fungus comprises two basic structures – mycelium and hyphae. Mycelium is a filamentous thallus and has contributed to the successful colonization of fungi in varied ecological niches. The mycelium comprises branching, microscopic tubular cells called hyphae. These hyphae can have cross-walls called septa or lack the cross walls – non-septate. The septa have pores – the septal pores for the passage of cytoplasm and organelles from one compartment to another. The type of hyphae and the complexity of the septal pores are the characteristics of each group of fungi. Fungi share a deep association with nature and its community.

Fungi are the essential and diverse component of the biodiversity of various ecosystems. They are both, beneficial and detrimental. They are responsible for numerous diseases of living beings and cause the spoilage of several perishable items. However, they play an important role in agriculture, and nutrient recycling in soil, industries, and pharmaceutical sectors. The extensive fungal study – Mycology, is difficult due to the high level of diversity and difficulty in the enumeration and estimation of global fungal species.

2 Applications

Fungi and Oil Spills

Oil spills are quite dangerous to nature, whether accidental or intentional as it comprises hydrocarbons that have a carcinogenic property and causes a deteriorating impact on the marine ecosystem, disturbing the marine food chain and threatening the marine community. Several chemical and physical methods are being employed to remove the oil spill from the ocean, however, each of the techniques has its own cons. Bioremediation of the oil spills by the utilization of native and non-native microbes to clean the oil spills has proven to be a promising technique globally. Though not in abundance, marine fungi have been found to have a greater capability of degradation of hydrocarbon (present in oils), and the field of mycoremediation is growing exponentially.

The crude oil finds its way into the environment basically, through two routes. One route is associated with human activities related to oil spill extraction, transportation, storage, refining, or destruction of the platform due to earthquakes or hurricanes. The second route is associated with the natural seepage of crude oil and tar from the bottom of the ocean owing to eroding of sedimentary rocks (Hunt, 1996).

The largest oil spills since 1967 globally are depicted in Figure 1.

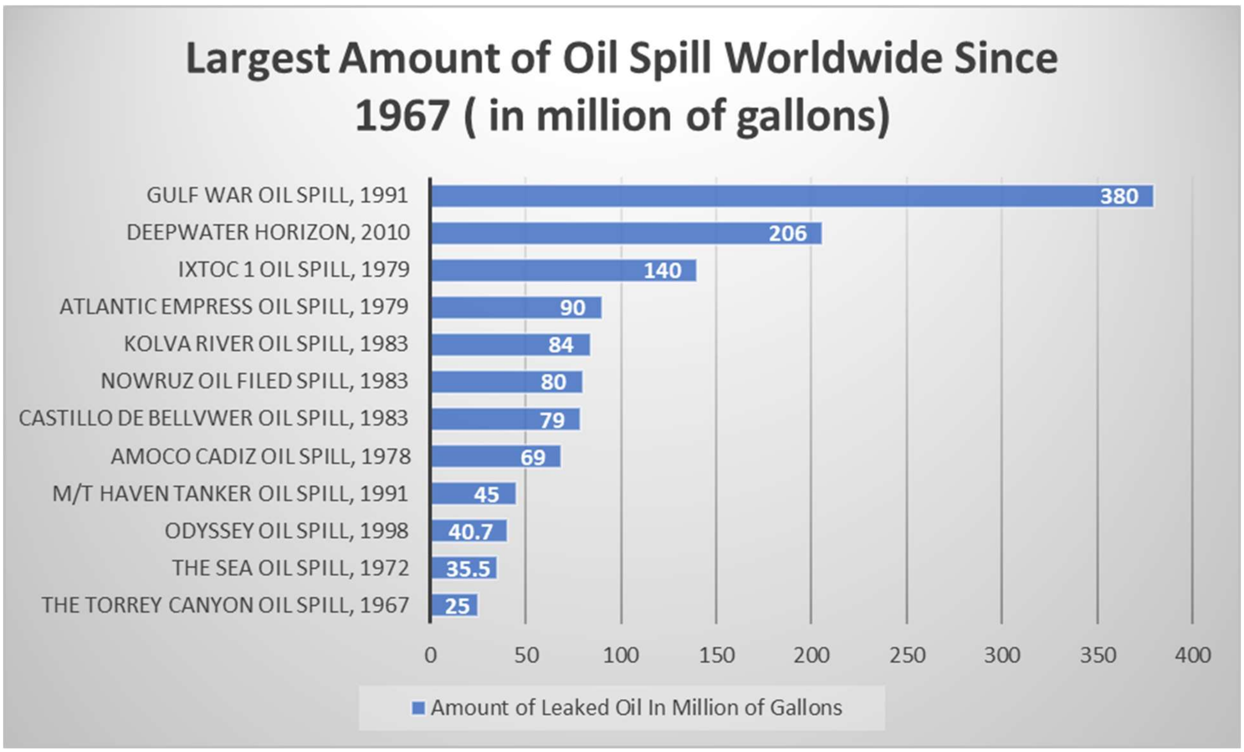

Figure 1. The Top 12 Largest Oil Spills Worldwide Since 1967. (Graphic by the author, with data sourced from Statista.com.)

Since 1967 there have been several devasting oil spills around the world. The largest was in 1991, at the time of the Persian Gulf War, where an estimated 380 to 520 million gallons of oil was intentionally spilled by the Iraqi forces into the Persian Gulf. The purpose of this act was to stop U.S. and coalition forces from landing. The incident developed thick oil slicks into the marine environment, some of which were as thick as five inches., causing the loss of marine biodiversity

Several microorganisms possess the ability to decompose petroleum oil fractions. The mixed cultures of bacteria and fungi largely degrade the oil. However, the single cultures of fungi are the better degraders of oil as compared to mixed cultures (Okerentugba & Ezeronye, 2003).

Mycoremediation.

A branch of bioremediation, utilizing fungi to degrade or remove the toxins from the environment is referred to as “Mycoremediation”. Fungi are highly skilled and capable of breaking down several long-chained toxins into simpler and less toxic chemicals. This potentiality of fungi is being used for the degradation of oil spills now. The major fungal phyla/subphyla involved in the bioremediation of oil include the Ascomycota, Basidiomycota, and Mucoromycotina, fungal genera including *Aspergillus*, *Candida*, *Cephalosporium*, *Penicillium*, *Torulopsis*, *Saccharomyces*, *Paecilomyces*, *Gliocladium*, *Yarrowia*, *Pleurotus*, *Pichia*, *Geotrichum*, *Talaromyces*, *Cladosporium*, *Mucor*, *Fusarium*, *Alternaria*, *Polyporus*, *Rhizopus*, *Rhodotorula*, *Aureobasidium*, *Hansenula*, *Rhodosporium*, *Trichosporon*, *Cunninghamella*, *Cyclothyrium*, *Mortierella*, *Psilocybe*, *Yarrowia*, *Beauveria*, *Verticillium*, *Drechslera*, *Geotrichum*, *Phialaphora*, and *Trysanophara* (Kumar & Kaur, 2018).

Likewise, mushrooms have higher biodegradability of hydrocarbons than bacteria and enzymes. The mushrooms growing on oil-contaminated piles not only absorb the oil but also release spores, attracted birds, aid pollination, and support the growth of new plants on the contaminated land.

Nutrient Cycling

Fungi can transform the nutrients in a way that could be easily absorbed by the plants. As stated earlier, fungi play a major role in the decomposition of plants and animals’ dead matter. These saprophytic fungi produce a broad-spectrum enzyme capable of degrading the organic matter of dead plants and animals, thereby releasing the mineral nutrient into soil-pore water and improving soil fertility. The fungi perform these degradative actions in close association with saprophytic bacteria and soil microbes.

Fungi release the degrading enzymes onto the substrate or remain bound outside the fungal cell wall. Several large organic molecules are broken down into simpler inorganic molecules and transported into the cell by an assembly of protein carriers in the cell membrane and utilized for their metabolic pathways. The product of their pathway is a simpler compound that can be easily absorbed by plants. For example, fungi break down the plant's complex components such as lignin and cellulose. The fungi specifically belonging to the class Agaricomycetes releases the enzymes such as lignin peroxidases (LiP), manganese peroxidases (MnP), or versatile peroxidases (VPL) for the degradation of lignin (Treseder & JT, 2015). The lignin is degraded into carbon dioxide and water which act as the source of nutrients for the plants. Thus, fungi play an important role in managing the earth’s C-cycle.

Similarly, broken down woody matter of plants and other surface waste by fungi releases nitrogen back into the soil in the form of ammonium nitrate, which is a nutrient that is needed for plant survival.

Mycorrhiza

A very specific symbiotic association is found between the fungi and the roots of higher plants and is referred to as “Mycorrhiza”. It is of two main categories: a) ectomycorrhiza and b) endomycorrhiza. Ectomycorrhizal fungi form the association with the plant's roots externally, while endomycorrhiza establishes the association within the cells of the host. Ectomycorrhizal fungi (EcMF) are largely involved in soil nutrient cycling in forest ecosystems. These fungi facilitate the uptake of nutrients such as nitrogen, phosphorus, and water by the host plants, improving the growth of the plant and providing resistance to stresses and diseases, thereby conserving the plants of the forest ecosystem. Simultaneously, EcMF obtains the carbon sources for their growth from the host plants. EcMF degrades the soil organic matter through enzymatic degradation, which promotes the carbon and nitrogen cycling in the forest soil (Liu, Li, & Kou, 2020). Likewise, EcMF releases several organic acids and phosphatases to enhance the availability of soil phosphorus or increase the mycelium spread to improve the plant's absorption of phosphorus. EcMF also aids in the seedling settlement, community restoration, and succession processes. The EcMF communities require wider exploration for their utilization under the present threat of climate crisis for the development of sustainable forest reserves.

Ectomycorrhizal fungi are majorly Basidiomycota and comprise common woodland mushrooms, such as *Amanita spp*., *Boletus spp*., and *Tricholoma spp.* Ectomycorrhizas can be very exceedingly specific such as Boletus elegans with larch and non-specific such as *Amanita muscaria* with 20 or more tree species. Likewise, forty fungal species can form mycorrhizas with pine (Moore, 2016). An example of Ectomycorrhizal association with the roots is depicted in Figure 2.

Figure 2. Ectomycorrhizal Fungi on the root of Beech Tree. (Image Credit: Pixabay.)

Ectomycorrhiza also helps to lower the climate crisis. The plants are the most efficient entity for sequestration of atmospheric carbon and serve as the front-line soldier to combat climate change. However, every plant dies, and stored carbon becomes part of the soil as they decompose. Therefore, the rate of carbon dioxide leaving the soil has a substantial impact on the concentration of greenhouse gases. Several researchers have found out that the soil colonized by the ectomycorrhizal fungi comprises as much as 70% of the carbon as compared to the soil containing the endomycorrhiza. This is due to the ability of ectomycorrhizal fungi to extract nitrogen more efficiently and rapidly than their fungi counterparts. As they absorb the nitrogen, it slows down their ability to degrade the dead plant matter, which in turn slows down the amount of carbon released back into the atmosphere and keeps it stored in the soil. Thereby, reducing the addition of more carbon into the atmosphere and lowering climate change.

As a well-known fact, the excess carbon dioxide in the atmosphere (the main culprit of the climate crisis), is well absorbed by the plants through the process of photosynthesis. However, 70% of the carbon in plants is transferred to roots, which in turn is stored in the fungal mycelium. This feeds the microbial life, earthworms, and nematodes and they start cycling the nutrients. Therefore, fungi play a major role in stabilizing carbon in the soil. Once the carbon is stable, it can be stored in the soil for thousands of years.

Endomycorrhiza forms the structure within the cortical cells of the plant roots and grows intracellularly. At the fungus-plant interface, the membranes of fungus and plants are in direct contact with each other. Endomycorrhiza is classified into arbuscular mycorrhiza (AM, formerly called vesicular-arbuscular mycorrhiza (VAM)), ericoid and orchid mycorrhiza. The AM fungi are recently classified into a separate phylum, Glomeromycota, and largely belong to four *genera Acaulospora, Gigaspora, Glomus*, and *Sclerocystis* (Marschner, 2012). Ericoid mycorrhiza can grow luxuriously in form of coils of hyphae within the epidermal cells of the roots of *Ericales,* with individual hyphae extending into the soil. Likewise, Orchid mycorrhiza are formed between plants of the family *Orchidaceae* and other diverse fungi. In orchids, the presence of mycorrhiza is critically important during seedling development. Orchid seeds practically lack energy reserves and their seedlings acquire the carbon from the fungal symbiont. Therefore, during the stage of symbiosis, the flow of C occurs from the fungus to the host which is significantly different from another mycorrhiza where C is supplied by the host plant to the fungus.

The major advantage of AM symbiosis for plants is for acquiring the phosphorus by the plants. In the process the AM fungi by their very effective AM pathway facilitate the scavenging of P in large volumes of soil and rapidly get delivered to the cortical cells within the roots, avoiding a low rate of direct uptake. The AM pathway greatly reduces the impact of Pi depletion from the soil and improves plant growth and P nutrition.

A few of the beneficial traits of AM are as listed:

- Improves the nutrition of the plants by aiding the development of the deep root system (Juwarkar, Juwarkar, & Khanna, 2004).
- Improves the soil structure by facilitating the binding of soil particles and microaggregates by external mycelium. (Miller & Jastrow, 1992).
- Restricts the growth of pests, thereby enhancing the resistance of roots to diseases and reducing the use of pesticides.
- Facilitates more even crop growth patterns and increases crop yield.
- Supports plants under drought-like conditions.
- Improves the hardiness of the transplanted stocks.
- Enhances the uptake of potassium, sulfate, copper, zinc, nitrate, and ammonium from the soil.

Fungi as Bicontrol Agent

The use of fungi as a biocontrol agent (BCA) has gained much attention and value. Fungal biocontrol agents do not cause any harm to the environment and do not develop resistance in several types of insects, pests, weeds, and pathogens, owing to their complex mode of action. They are surely a better alternative to chemical pesticides. The fungal BCA need not be ingested by the host insect, but fungi can invade the host insects directly through the insect's cuticle and can control all insect pests including sucking insects. Fungi also act by direct antagonism (Hyperparasitism), antibiosis, competition, or induced resistance.

Hyperparasitism is the process in which the parasitic fungi are killed by the fungal BCA. For example, *Trichoderma lignorum (T.viride)* controls the damping-off of citrus seedlings by parasitizing the hyphae of *Rhizoctonia solani* (Savita & Sharma, 2019).

Fungal BCA also operates via antibiosis. Antibiosis refers to the process by which the pathogenic organism is killed by the metabolic product produced by fungi. For example, *Trichoderma pseudokoningii* and *T. viride* kills *Botrytis cinerea* on strawberry fruits by producing some secondary metabolites (Tronsmo & Dennis, 1977).

Competition is a process in which two organisms compete for nutrients for their survival. Fungal BCA can establish competition with the parasitic organisms, thereby killing them. For example, some species of filamentous fungi and yeasts restrict the growth of fungal pathogens by reducing the concentration of nutrients which results in reduced spore germination and slower growth of germ tubes in the pathogenic fungi. Likewise, *Trichoderma* significantly restricts the growth of *Pythium* and *Fusarium oxysporum* in the soil by competing for available iron in the soil (Tjamos, Papavizas, & Cook, 1992).

Induced resistance is one of the most important modes of biocontrol in plants against soilborne and foliar pathogens. Induced resistance limits the growth and spread of pathogens by secreting defense-related enzymes such as chitinases, proteases, and peroxidase (Hammerschmidt, Nuckles, & Kuc, 1982). For example, Salicylic acid produced by T39 of *Trichoderma harzianum* induced resistance against *Botrytis cinerea* in beans (De Meyer, Bigirimana, Elad, & Höfte, 1998).

Likewise, fungal BCA act on nematodes by trapping them by their hyphae and invading the body cavity of nematode, resulting in their death. Some of the fungi that control nematodes include *Dactyella* and *Arthrobotrys, Lagenidium*, etc. (Savita & Sharma, 2019).

Several mycoherbicides control the weeds and include *Alternaria cassiae, Cercospora rodmanii, Colletotrichum coccodes, Chondrostereum purpureum, Phytophthora palmivora etc.* (Savita & Sharma, 2019).

Several Advantages of fungal BCA are depicted in Figure 3.

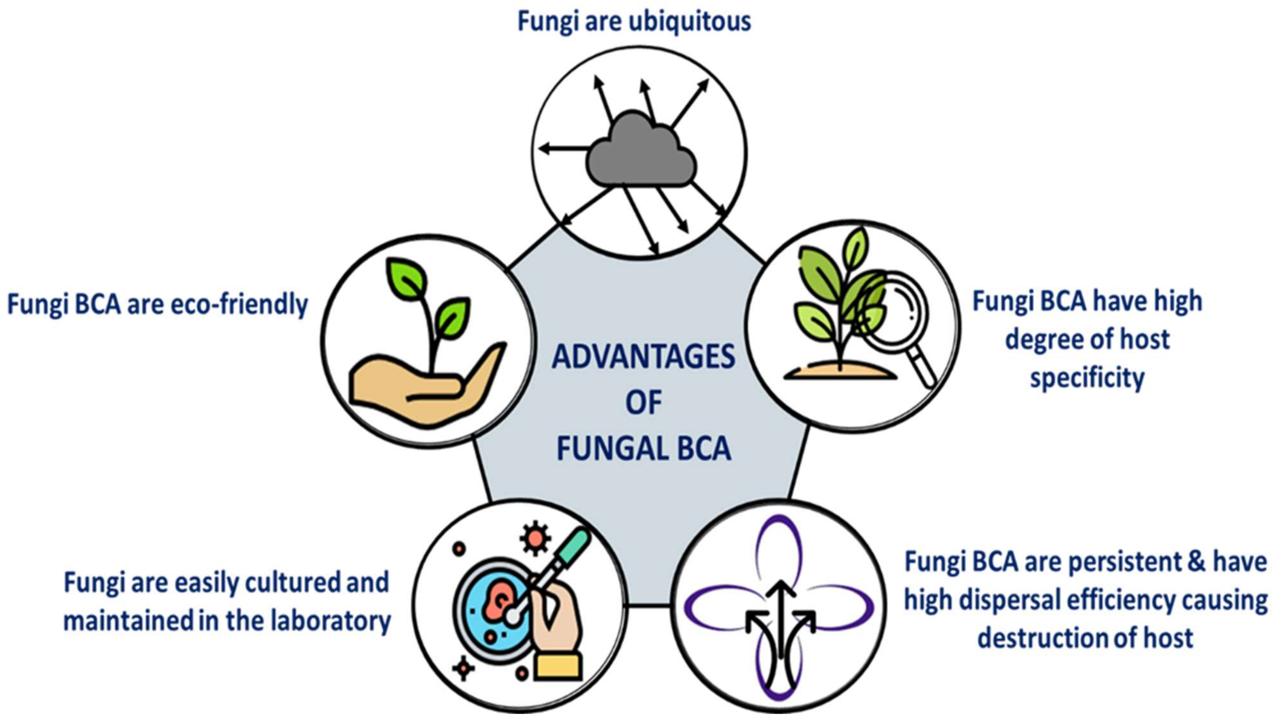

Figure 3. Advantages of Fungal BCA (Illustration by the author, after Savita & Sharma, 2019)

Fungi as Food

Fungi are considered ideal food due to the high level of protein content (10-30 % dry matter as crude protein) and comprise all the essential amino acids for human and animal nutrition (Moore & Chiu, 2001). Fungal biomass is a promising source of dietary fiber and is practically free of cholesterol. Furthermore, these fungi have a significant quantity of carbohydrates and fiber, vitamins (such as thiamine, riboflavin, cobalamin, vitamin C, and D), and minerals (Se, Cu, Mg, Na, K, P, Fe, Ca, and Mn).

Fusarium is utilized for fermenter-grown fungal foods and forms a healthy alternative to meat. Similarly, mushrooms have been utilized as food for several decades. The global mushroom market is estimated to account for a value of USD 16.7 million in 2020 and is exponentially increasing.

Cultivation of fungi with minimum energy inputs

The fungi can be easily cultivated on the waste material substrate, thereby, decreasing the cost of their cultivation. For example, oyster mushroom species are readily cultivated on cotton wastes. Likewise, the straw mushroom *Volvariella volvacea* can also be cultivated on the cotton waste generated by the textile and garment industries. *Pleurotus spp.* readily grow on several lignocellulosic agricultural wastes. Disposal of bulky solid waste coupled with earning potentiality is a good example of an organic farming system integrated with the waste management system. Furthermore, after the mushrooms have been harvested, the 'spent compost' finds its place as a potential animal feed (the mushroom mycelium enhances the protein content), as a soil conditioner as well as the digester of pollutants such as polychlorinated phenols on landfills waste sites (Moore & Chiu, 2001). The Oyster mushroom can even grow on the biosolids obtained from an anaerobic digester. Equally, substrates can be harvested from neighbouring forests (through sustainable forest management), recycled agricultural residues, sugarcane factories, livestock feed, and the mulberry industry (Hyde, et al., 2019).

The reliable substrate sources and the appropriate techniques are the only two major factors for the successful cultivation of the fungi/mushrooms. The inputs/substrates required for the cultivation process are quite simple and readily obtained at a cheaper rate. Likewise, mushrooms can be cultivated by different methods such as using sawdust bags, bottles, shelves, and logs. Additionally, the infrastructure required for mushroom cultivation only includes an enclosed and well-sterilized room with well-maintained humidity, temperature, uniform ventilation, appropriate substrate moisture levels, and or light for the formation of fruiting bodies. This provides all most all the necessary environmental requirements for mushrooms to grow. The energy requirements (in terms of electricity and water) can be contributed by renewable sources of energy (for example solar panels and reuse of treated wastewater).

A wide range of fungi can be used as food, as a healthy alternative to carbohydrates and fats-rich foods, as shown in Table 1, below.

Sr. No.	Types of Foods	Fungal Species
1.	Button Mushroom	*Agaricus bisporus*
2.	Shiitake	*Lentinula edodes*
3.	Straw mushroom	*Volvariella volvacea*
4.	Winter mushroom	*Flammulina velutipes*
5.	Oyster mushroom	*Pleurotus spp.*
6.	Truffle	*Tuber melanosporum*
7.	Roquefort cheese	*Penicillium roquefortii*
8.	Camembert cheese	*Penicillium camembertii*
9.	Ang-kak (type of rice used in China)	*Monascus purpureus*
10.	Hamanatto (Japanese delicacy)	*Aspergillus oryzae*
11.	Miso (Japanese Seasoning)	*Aspergillus oryzae, A. sojae*
12.	Ontjom (Indonesia Cusine)	*Neurospora intermedia*
13.	Soy sauce	*Aspergillus oryzae, A. sojae*
14.	Tempeh (Indonesian food)	*Rhizopus oligosporus*

Table 1. Global Fungal Foods (Moore & Chiu, 2001)

Most of these mushrooms are grown near their point of sale. Otherwise, preserved mushrooms are imported as canned or dried products in most global regions. For example, the UK imports most of its mushrooms from the Netherlands or Ireland. Similarly, Hong Kong imports most of its mushrooms from China, Taiwan, and Japan (Moore & Chiu, 2001). The total percentage of the worldwide production of edible mushrooms by genus is depicted in Figure 4.

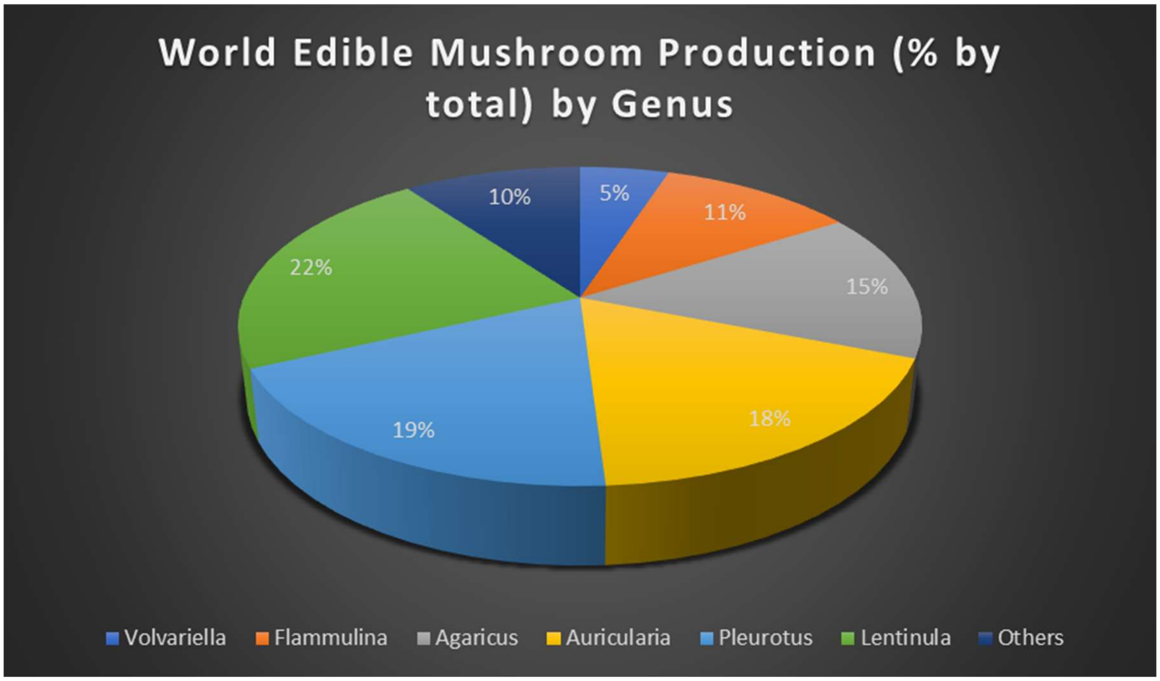

Figure 4. World Edible Mushroom Production (% by total) by Genus. (Riaz, et al., 2022)

Similarly, yeasts, the unicellular fungi, play a vital role where biotechnology is applied to the food industry (brewing and bread-making) and serve as the source of single-cell protein and dietary supplements. Yeasts are those magical microbes that are involved in the production of wine relished globally. The global consumption of wine in 2020 was recorded to be 234 million hectoliters, as per the International Organization of Vine and Wine. The wide variety of wine available globally is not only due to more than 5000 varieties of grapes but specifically due to the location, soil, climate, and fermentation conditions. Yeasts – *Saccharomyces cerevisiae* – the most vital component of wine production contributes to the fermentation process. This yeast consumes the available sugars from the grapes and undergoes a fermentative pathway to produce alcohol as the by-product. The by-product is refined and purified to obtain highly desirable wine. Likewise, the selection of indigenous species of yeast is currently being promoted to conserve the typical quality and taste of the regional wines. However, several undesirable epiphytic yeasts such as *Candida, Hanseniaspora, Kloeckera, Metchnikowia, Pichai, Rhodotorula, Torulopsis, Trichospora spp.* are usually suppressed by the addition of sulfur dioxide.(Nout, 2004). However, to restrict the utilization of chemical additives, starter cultures producing killer toxins are a promising alternative to deal with the spoilage yeasts during wine production. Therefore, the use of *S. cerevisiae* killer yeasts with desired fermentation properties is inevitable for a successful fermentation process (Mendoza, Fernández de Ullivarri, & Raya, 2018).

Fungi possess a unique ability to upgrade the nutritive value of industrial and agro-processing by-products (such as starch-containing sweet potato residues or cellulosic sugarcane bagasse (Yang, Jang, Liew, & Preez, 1993) as they can degrade the carbohydrate matter. A cheap nitrogen source such as $(NH_4)_2SO_4$ and urea added, can be converted into protein thereby improving the final food product after fermentation. Fungi such as *Aspergillus niger, Rhizopus spp*., and *Neurospora sitophila* are widely used for the protein enrichment of starchy foods and feeds (Nout, 2004).

A type of cultivated mushroom - *Ganoderme lucidum* (figure 5) is largely cultivated in China. It has more pharmaceutical properties as compared to other species of mushrooms. It has a long history of use for promoting health and longevity in China, Japan, and other Asian countries (Wachtel-Galor, Yuen, & Buswell, 2011). *G. lucidum* is used to produce several health drinks, powders, tablets, capsules, and diet supplements. (Moore & Chiu, 2001).

Figure 5. Ganderma lucidum. (Image Source: Pixabay.)

The global market for alternative proteins is growing widely. Mycoprotein from the fermented mushroom is a promising meat-free alternative. Meat-free proteins are environment-friendly and have a reduced carbon footprint. They can create a more sustainable food system. Likewise, several substituents for sausages and chicken are made from soy, pea, and other protein. The high nutritive value of several edible mushrooms (Table 2) has largely attributed to their high consumption globally and their images are depicted in Figure 6.

Sr. No.	Nutritional Parameter	Mushrooms			
		Agaricus bisporus	*Pleurotus Spp.*	*Volvariella volvacea*	*Lentinula edodes*
1.	Protein (%)	29.14	19.59	38.10	18.85

2.	Carbohydrates (%)	51.05	64.34	42.30	63.60
3.	Fat (%)	1.56	1.05	0.97	1.22
4.	Vitamin D (IU/g)	984	487	462.04	205
5.	Sodium (mg/kg)	500.8	208.87	345.34	82.49
6.	Potassium (%)	4.21	2.70	4.16	2.10
7.	K: Na	84:1	129:1	120:1	255:1
8.	Iron (mg/kg)	85.86	183.07	72.51	37.55
9.	Manganese (mg/kg)	7.97	6.47	-	17.48
10.	Zinc (mg/kg)	79.64	162.18	94.28	89.63

Table 2. *Nutritional Valve of a few edible mushrooms used globally (on a dry weight basis) (Gupta, Summuna, Gupta, & Annepu, 2019).*

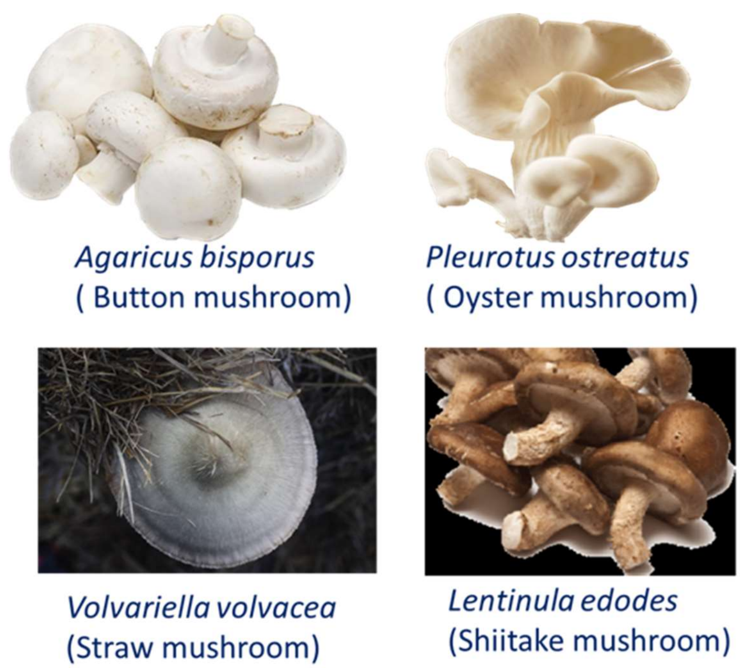

Figure 6. Some widely used edible mushrooms.

The food industry utilizes several varieties of synthetic colorants to enhance the “appeal factor” of the food. However, these synthetic colorants though cheap, have many ill-health impacts. These synthetic colorants are now replaced by various pigments obtained from plants. However, the production processes of plant-based pigments are limited due to plant growth needs. On the contrary, filamentous fungi can be grown readily and on a large scale in the fermenters and form an important source of pigments. For example, *Mycena sanguinolenta* produces blue pigment (Sanguinone A) (Peters & Spiteller, 2007). *Cholorociboria aureginosa* produces green pigment (Xylindein) (Saikawa, Watanabe, Hashimoto, & Nakata, 2000). The pigments can be produced at a large scale in bioreactors, with relatively shorter fermentation times, and offers a cost-efficient approach to obtaining several colorants (Hyde, et al., 2019).

Fungi are not only used as a colorant but have the potential to enhance food flavour. For a long time, plant extracts were utilized as flavour and fragrance enhancers. Likewise, even the compounds such as aldehydes, esters, methyl ketones, and terpenoids obtained from microbial fermentation are utilized as flavouring agents. Vanillin – the first synthetic flavour and fragrance compound in the food industry was produced back in 1874, by utilizing two filamentous fungi through bioconversion. (Lesage-Messen , Delattre, Haon, & Thibault, 1996). The first step involved the conversion of ferulic acid into vanillin acid using *Aspergillus niger and the second step involved the reduction of vanillin acid to vanillin by Pycnoporus cinnabarinus.* Similarly, during the amino acid catabolism in yeast, banana flavor (due to isoamyl alcohol) and (rose-flavor) (due to 2-phenyl ethanol) are produced naturally (Ravasio, Walter, Trost, Vrhovsek, & Wendland, 2014). A few more examples of fungi synthesizing the flavoring agents include a) *Zygosaccharomyces rouxii* produces Furaneol (caramelly type odor) (Hecquet, Sancelme, Bolte, & Demuynck, 1996), *Yarrowia lipolytica* produces γ-Decalactone (woody-type flavour) and *Kluyveromyces sp.* Phenylethanol (rosary-like flavour) (Gupta, Prakash, & Gupta, 2015). However, several explorations concerning gene modification constituents the prospects of exploiting fungi as the flavouring agent.

Fungi as Medicine

Fungi are not only utilized as functional foods but also possess medicinal value. Some molds and fungi are the source of Penicillin, Griseofulvin, Lovastatin, Streptomycin, etc., and other medicines. Penicillin is the most famous and widely used antibiotic obtained from the fungus *Penicillium.* Likewise, Cephalosporin produced by *Acremonium sp.* targets the gram-positive bacteria and lessens their infections. A few more examples of antibiotics produced by fungi are listed in table 3.

Sr. No.	Name of Antibiotics	Produced fungi	Target Organisms
1.	Griseofulvin	*P. nigricans* *P. griseofulvum*	Fungi
2.	Citrinin	*P. citrinum*	Fungi
3.	Palutin	*P. palutum*	Fungi and bacteria
4.	Fumagillin	*Aspergillus fumigatus*	Protozoa
5.	Fusidic acid	*Fusidium coccineum*	Bacteria
6.	Viridin	*Trichoderma viridi*	Fungi

Table 1 List of Antibiotics and Their Fungal Producers (Ghasem, 2007)

A mould called *Claviceps purpurea* produces ergotamine and LSD (lysergic Acid Diethylamide). Ergotamine in combination with caffeine can be used for relieving migraine headaches. LSD is utilized in the treatment of anxiety, depression, psychosomatic diseases, and addiction. Some fungi such as *Nodulisporium sylviforme* and *Taxomyces andreanae* are effectively utilized to produce anticancer drug paclitaxel (Qadar & Zafar, 2011). One of the fungal products Cyclosporin is widely used as an immunosuppressant during organ transplants. It avoids organ rejection and improves the success rate of transplant operations (Moore D. , 2001). Similarly, another fungal product – gliotoxin helps in the regulation of the immune system in the postoperative management of transplant patients. Fungus *Aspergillus terreus* produces a hydroxy-acid compound – mevinolin which acts as a cholesterol-lowering agent by hindering the enzymes that make cholesterol in mammals (Moore D. , 2001).

Several fungi produce metabolites that inhibit the multiplication of viruses in culture and animal tests. These fungal compounds effectively act against the major disease-causing viruses like poliovirus, coxsackievirus, vaccinia, and various influenza viruses.

Aphidicolin – a tetracyclic diterpene, isolated from *Cephalosporium aphidicola* possesses antiviral and antimitotic properties. Aphidicolin competes for the particular binding site on DNA polymerase α, δ, and ε enzymes (Hyde, et al., 2019). Its mechanism and anticancer property have been intensively studied in a clinical trial, however, the drug is yet to be marketed. Other anticancer compounds obtained from fungi – *Leptoshaeria sp*. include leptosins F and C, which illustrate antitumor activity in mouse embryos (Yanagihara, et al., 2005). *Trichoderma viride* has been successfully utilized to produce 10 mm spherical silver nanoparticles which illustrates cytotoxicity toward human cervix carcinoma Hep-2C cells (Adebayo-Tayo, Ogunleye, & Ogbole, 2019). Similarly, the nanoparticles of zinc oxide and chitosan were produced by *Trichoderma harzianum* and effectively utilized against human lung carcinoma A549 (Saravankumar, et al., 2020). Additionally, *Trichoderma species, T. atroviride* produced silver nanoparticles have shown in vitro efficacy against breast cancer. Saccharomyces cerevisiae produced beta – glucan are utilized for the synthesis of doxorubicin-loaded nanoparticles which are used in the treatment of breast cancer.

Many Basidiomycota like Agaricus *bisporus*, *Cyclocybe aegerita, C. cylindracea* and *Tremella fuciformis* are effectively used as medicine for the treatment or prophylaxis of type 2 diabetes. These mushrooms avoid the high levels of glucose in diabetic patients and they contain the least amount of digestible carbohydrates in the diet (Poucheret, Fons, & Rapior, 2006). The fruiting bodies of *Antrodia cinnamomea* are used industrially to produce healthy foods and drugs that have anti-diabetic properties (Huang, Wang, Nguyen, & Kuo, 2018). Evenly, *Grifola frondosa* has been utilized for type 2 diabetes and its extract can have an impact on both – hyperglycemia and hyperinsulinemia (Poucheret, Fons, & Rapior, 2006). Some of the medicinal mushroom products are also used as remedies for diabetes, for example, the *Ophiocordyceps sinensis* capsules and ReishiMax capsules decrease fasting blood glucose in type 2 diabetes. These medicines are also known to reduce blood pressure and body weight (Hyde, et al., 2019). The medical product – *Tremella* obtained from *Tremella fuciformis* reduces blood glucose and cholesterol levels significantly (Li, Zheng, Bukuru, & De Kimpe, 2004).

Mushrooms, such as *Antrodia camphorata, Ganoderma* spp., *Hericium erinaceus*, *Lignosus rhinocerotis* and *Pleurotus giganteus*, are proven in enhancing the peripheral nervous system, and a potential candidates for the treatment of Alzheimer's, Huntington's, and Parkinson's disease (Hyde, et al., 2019). Mushrooms are thought to play a vital role in psychedelic treatment and in curing depression.

Mushroom extracts can also lower the levels of Estrogen and Testosterone hormones by inhibiting the enzymes aromatase and 5-alpha reductase (Chen, et al., 2006).

Some of the other beneficial uses of mushrooms are as listed:

- Rich in proteins, B-complex vitamins, and minerals, which are essential for the general growth and development of the body.
- Prevents the spread of tumor cells and AIDS.
- Effectively treats cold, stomach/headaches, and hepatitis B.
- Confers a positive impact on diseases like arteriosclerosis, kidney failure, and high blood pressure.
- Delays aging.
- Produce enzymes such as Pepsin and Trypsin aiding the treatment of gastric diseases.
- Produce enzymes such as asparaginase, which forms a part of leukaemia treatment in children.
- Rich in ergosterol (provitamin D2), which can change to vitamin D2 under sunlight. Vitamin D2 aids the development of bones and muscles preventing rickets.
- Rich in folic acid and thereby used for the treatment of anaemia.
- Contains low levels of sodium and potassium, thereby suitable for people with hypertension, diabetes, and obesity.
- Contains high levels of anti-oxidants preventing the onset of cancer, and heart diseases.

(Source – modified from Qadar & Zafar, 2011)

However, future investigation is required to clarify the long-term effects of taking medicinal mushroom products with other drugs.

3 Cultivation of Fungi and Ideal Growth Parameters

Submerged cultivation and solid-state cultivation are the two majorly utilized techniques to produce fungi and their metabolic products. These methods are widely used for the cultivation of fungal biomass.

Submerged cultivation involves the growth of fungal biomass in a liquid medium with adequate water and dissolved nutrients, while solid-state cultivation is carried on by culturing the fungal biomass on the solid substrate, with appropriate moisture content to support fungal growth. Examples of some of the solid substrates utilized include rice straw, sugar beet pulp, apple pomace, orange peel, agricultural waste, etc. Solid-state cultivation has a lower energy requirement and is far more cost-effective as compared to submerged cultivation. However, the control of process parameters and harvesting of fungal biomass, are more challenging than submerged cultivation, due to uneven distribution of fungal biomass, nutrients, moisture, temperature, and pH.

In submerged cultivation, bioreactors (a cylindrical vessel) with a mechanical stirrer are utilized. Some bioreactors utilized for the growth of fungal biomass include; a) stirred tank reactor (STR) b) airlift reactor (ALR) and c) bubble column reactor (BCR). Agitation in the bioreactor is an essential parameter that influences shear force as well as mass and heat transfer in the bioreactor (Barzee, Cao, Pan, & Zhang, 2021). Dissolved oxygen is often a growth-limiting factor due to its low solubility in media and high uptake rates by microorganisms. Therefore, for the constant fungal growth, the level of dissolved oxygen must be monitored and controlled.

Fungi grow at a wide pH range. However, at different pH fungi illustrates different morphologies. For example, *A. oryzae* at pH below 3.5 shows filamentous morphology, at pH 4.0-5.0 shows filamentous + pellet growth, and at pH above 6.0 illustrates pellet growth (Carlsen, Spohr, & Nielsen, 1996).

Temperature is another vital environmental parameter that stimulates fungal growth. Most fungi are mesophilic and grow luxuriously in the temperature range of 5 – 35˚C. However, the optimal growth temperature normally ranges between 25 – 30˚C. The thermophilic fungi survive at temperatures above 40 ˚C (Magan, 2007).

The harvesting of fungal biomass is quite simple as compared to the harvesting of microalgae and bacteria as fungi hyphae/pellet are larger in size. The harvesting is generally done by simple sieves or screens with proper openings which capture the mycelium or pellets. At a large scale, filtration and centrifugation are also utilized (Nigam & Singh, 2014).

The media of cultivation for fungi must include organic matter as their energy and carbon source. Likewise, fungi also require several macronutrients (such as carbon, oxygen, hydrogen, nitrogen, phosphorus, potassium, sulphur, and magnesium) and micronutrients (such as manganese, iron, zinc, copper, and molybdenum). The commonly used carbon source includes sugars such as glucose, fructose, and sucrose which are rapidly taken up by fungi. Additionally, lignocellulosic biomass can be utilized for the growth of fungal biomass. Fungi can also be cultivated on several agricultural by-products.

4 Conclusion

Fungi are interesting organisms with a high growth rate on the minimal available substrates. They are the important decomposers of the ecosystem. They are in sync with nature and communicate with it. Fungi are explored in several ways for the benefit of mankind. From being decomposers to the future foods they are ubiquitously present. They can strive in extreme environmental conditions naturally and likewise be cultured quite easily in the laboratory. Mushroom a well-known edible fungus is used largely around the world due to its health benefits and ease of cultivation without much investment. Apart from manifesting human health benefits, fungi also improve the health of the soil and thereby enhancing the growth of the crops. They are a rich source of protein and a potent candidate for replacing red meat. Several exploration and studies are still undergoing to thoroughly understand the magic of fungi, thriving beneath us.

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